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14. ABSTRACT Actual flight-based test and evaluation of vertical take-off reusable launch vehicles (RLVs) has been dormant in the U.S. since the end of the SDIO/NASA/McDonnell Douglas Delta Clipper - Experimental Advanced (DC-X/XA) project in 1996. A joint industry-academic team working under sponsorship from the Air Force Research Laboratory's Propulsion Directorate took a small step in 2005 towards re-invigorating such RLV test and evaluation activities, using an early, low-fidelity prototype of the first stage for a proposed nanosat launch vehicle (NLV) that is sized to deliver up to 10 kg into low Earth orbit. This team developed the LOX/ethanol Prospector 7 (P-7) in only six months and then flew it twice in a period of 3.5 hours after just eighteen hours of field site preparations. This compares to the twenty-six hour turn-around benchmark achieved with the DC-XA at the White Sands Missile Range. The P-7 has since been employed on a third flight test and is now undergoing preparation for its fourth mission later this year. In addition to supporting NLV development, it is anticipated that the results and lessons learned from these demonstrations of responsive, rapid RLV turn-around operations could also prove to be of relevance to the Air Force's ongoing investigations into hybrid launch vehicle concepts.					
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RLV Flight Operations Demonstration with a Prototype Nanosat Launch Vehicle (PREPRINT)

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Actual flight-based test and evaluation of vertical take-off reusable launch vehicles (RLVs) has been dormant in the U.S. since the end of the SDIO/NASA/McDonnell Douglas Delta Clipper - Experimental Advanced (DC-X/XA) project in 1996. A joint industry-academic team working under sponsorship from the Air Force Research Laboratory's Propulsion Directorate took a small step in 2005 towards re-invigorating such RLV test and evaluation activities, using an early, low-fidelity prototype of the first stage for a proposed nanosat launch vehicle (NLV) that is sized to deliver up to 10 kg into low Earth orbit. This team developed the LOX/ethanol Prospector 7 (P-7) in only six months and then flew it twice in a period of 3.5 hours after just eighteen hours of field site preparations. This compares to the twenty-six hour turn-around benchmark achieved with the DC-XA at the White Sands Missile Range. The P-7 has since been employed on a third flight test and is now undergoing preparation for its fourth mission later this year. In addition to supporting NLV development, it is anticipated that the results and lessons learned from these demonstrations of responsive, rapid RLV turn-around operations could also prove to be of relevance to the Air Force's ongoing investigations into hybrid launch vehicle concepts.

I. Introduction

AFTER a period of renewed interest and support in the mid and late 1990s, flight-based test and evaluation of reusable launch vehicles (RLVs) in the United States became dormant as difficulties arose and launch vehicle research priorities shifted to other missions and concepts. An attempt is now underway to re-invigorate such RLV flight research by adopting the incremental approach to vehicle development and phased testing that was successfully employed for the Delta Clipper program (DC-X/XA), which featured a prototype vertical take-off/vertical RLV.¹ This new program is initially focusing on the operational aspects of and metrics associated with conducting responsive, fast turn-around flights using an RLV prototype that is based on the first stage of a proposed nanosat launch vehicle (NLV). Key achievements to date include conducting two flights with this vehicle within a period of 3.5 hours (Figure 1). Almost as noteworthy is that this test article - the Prospector 7 (P-7) - was developed and entered flight just six months after authority to proceed was given under a Phase I Small Business Innovation Research (SBIR) contract from the Air Force Research Laboratory's Propulsion Directorate to a team lead by Garvey Spacecraft Corporation (GSC) and research partner California State University, Long Beach (CSULB).² Furthermore, on just its third flight, the P-7 helped make further progress towards RLV commercialization by generating revenues for manifesting a technology payload - a rarity in the history of RLV development so far.

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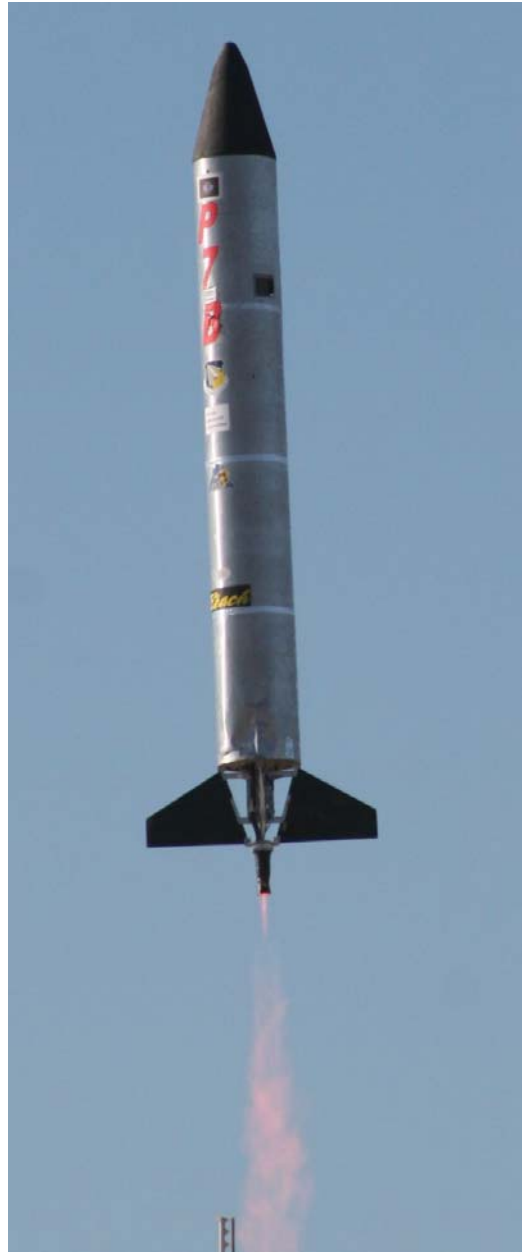


Figure 1. RLV Fast Turn-Around Flights - Twice Within 3.5 Hours on 29 October 2005

II. Background

GSC and CSULB have participated in joint research since early 2001 under the California Launch vehicle Education Initiative (CALVEIN). Since 2004, these activities have included the development and initial flight testing of full-scale, low-fidelity prototypes of a proposed expendable NLV that is designed to deliver up to 10 kg of payload to a polar, circular orbit of 250 km.^{3, 4} The Prospector 5 (P-5) first demonstrated launch operations and recovery with an NLV-sized first stage (Figure 2).⁵ The Prospector 6 (P-6) that followed incorporated the P-5 stage and structural simulators for the interstage and second stage to achieve the full scale of the NLV (Figure 3), while also featuring stage separation and improved landing techniques.⁶



Figure 2. Prospector 5 - Initial NLV Flight Test Prototype



Figure 3. Prospector 6 - Full Scale Prototype NLV in Flight

For both the P-5 and P-6 tests, vehicle recovery using parachutes was a secondary mission objective. The primary motivation for attempting it was to salvage high-value components for reuse in future test vehicles. This has been the standard CALVEIN operating philosophy since the first flight test with the Prospector 1. However, the demonstrated success in recovering vehicles of this size intact provided the basis for discussions on whether the turn-around refurbishment tasks could be compressed sufficiently to attempt two flights within a single 24 hour period. Candidate modifications to both the basic vehicle design and associated operations ultimately manifested themselves in the P-7 RLV fast turn-around demonstration project.

III. Project Objectives

The primary programmatic objective was to conduct a flight test demonstration of rapid turn-around RLV operations as early as was feasible within the constraints of a SBIR program. Leveraging of the existing CALVEIN hardware and operations made it possible to attempt this during Phase I, whereas more typically hardware testing would not occur until Phase II or even later when additional non-SBIR resources become available.

Table 1 identifies the top-level Phase I mission test objectives. Instead of focusing on advanced vehicle designs and technologies during this initial phase, the study, acquisition and assessment of operational metrics was given top priority, along with the identification and pursuit of opportunities for minimizing costs.

Table 1. RLV Demonstrator Flight Test Mission Objectives

Primary Objectives	Status
Conduct two flight tests within a 24 hour period using the same prototype RLV	Conducted within 3.5 hours
Monitor and measure key design and operational parameters associated with rapid turn-around launch activities	Completed
Secondary Objectives	
Acquire vehicle dynamic and performance data while in flight	Acquired using Montana State University (MSU) data logger
Manifest academic payloads	four academic payloads manifested, with two - the Cal Poly SLO* Poly-Picosat Orbital Deployer (P-POD) and the MSU data logger - functioning nominally on both flights

* California Polytechnic State University, San Luis Obispo

IV. Prospector 7 Prototype RLV

Figure 4 identifies the primary P-7 elements and specifies its overall dimensions.* The vehicle is passively guided, with recovery implemented through a redundant pair of on-board accelerometers that control the deployment of a pilot parachute that in turn extracts a main parachute from the side of the first stage. The P-7 lands fairing-first, with both the fairing and interstage absorbing the initial shock so as to minimize damage to the reusable first stage.† For rapid turn-around operations, the fairing and interstage are removed and replaced in the field and then subsequently refurbished back in the CSULB lab for reuse in future flights. After this initial impact, the vehicle then pivots until the aft end of the first stage reaches the surface, at which point the fins making contact and their associated struts deform to absorb the remaining kinematic energy. These and the engine chamber are replaced at the same time that the servicing activities at the forward end of the stage are underway.

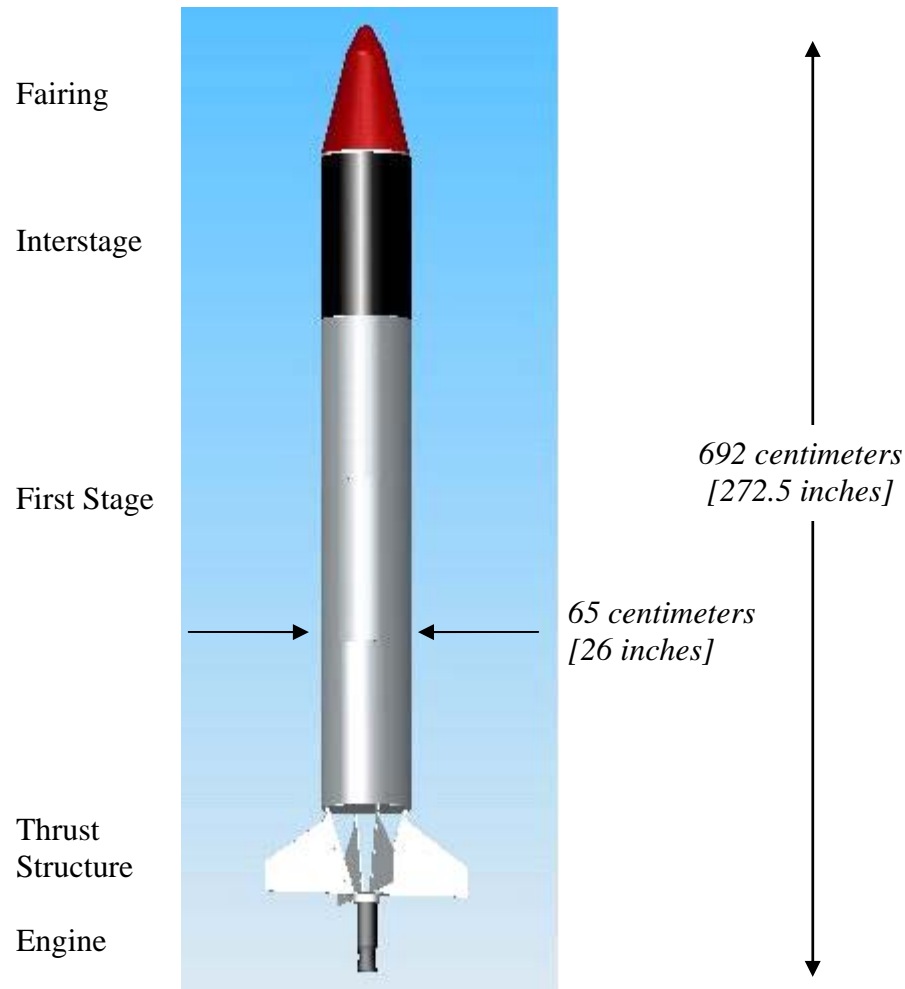


Figure 4. P-7 Vehicle Elements

* For hardware configuration management reasons, the initial two flight configurations for the RLV rapid turn-around demonstration were designated Prospector 7A (P-7A) and Prospector 7B (P-7B), respectively. Subsequent flights (i.e.- Prospector 7C, 7D) are identified by increments of the appendix letter.

† The term "interstage" was retained from the P-6 to refer to the P-7's skin and stringer structure mounted between the first stage and payload fairing. Whereas this structure did indeed serve as an interstage between the P-6 first stage and its simulated second stage, on the P-7 its function as noted above is to absorb loads during landing and on occasion manifest mission-specific payloads.

The P-7's LOX/denatured ethanol propulsion system is based on the 1200 lbf-thrust ablative engine employed previously on the P-5 and P-6 and is compatible with a gross liftoff weight (GLOW) on the order of 300 lbm. However, to both motivate the structures team and maintain technical margin, the initial P-7 design GLOW target was set for 270 lbm. Ultimately, the P-7 GLOW for the first two flights came in at just under 290 lbm, of which 25.6 lbm was payload.

As noted in Table 1, a secondary mission objective was to continue the manifesting of academic payloads. Since its beginning, an important CALVEIN contribution to the space community has been to provide launch opportunities to academic organizations that usually otherwise have to wait years for a secondary payload spot aboard a large orbital launch vehicle. The first two P-7 flights maintained this tradition with a total of four such payloads (Table 2). Two of them - the Montana State University (MSU) data logger (Figure 5) and the Poly-Picosat Orbital Deployer (P-POD) provided by California Polytechnic State University, San Luis Obispo (Cal Poly SLO) (Figure 6) functioned nominally on both flights. The MSU experiment provided important data on flight environments, while the Cal Poly SLO P-POD successfully ejected a set of three simulated "CubeSats" on each flight.⁷ As an added bonus, in contrast to most sounding rocket-based projects, the participating student investigators were able to return to their home campuses with their experimental hardware still in hand, ready for another round of testing.

Table 2. Academic Payloads Manifested on the P-7

Experiment	Objectives	Provider	Comments	Location
Mini-DV Camera	acquire in-flight video for post-flight recovery	CSULB	similar to video imaging experiment flown on P-6	aft bulkhead of first stage
Wi Fi-based IMU/GPS Telemetry Package	acquisition and real-time downlink of 6-degree-of-freedom dynamic data, tank pressures and break wire inputs	CSULB	derived from P-6 Wi Fi telemetry experiment, now includes O-Navi Phoenix IMU/GPS unit	dedicated bulkhead at the forward end of first stage, above the liquid oxygen (LOX) tank assembly
Data Logger	acquire vehicle environments and flight dynamics data for post-flight recovery	MSU	enhanced version of MSU data logger flown on P-6	aft bulkhead of first stage
Prototype P-POD	demonstrate CubeSat integration and deployment	Cal Poly SLO	features P-POD similar to that which will fly on Dnepr launcher	dedicated bulkhead at the aft end of the interstage



Figure 5. Montana State University Data Logger



Figure 6. Students with Cal Poly SLO P-POD CubeSat Deployer Mounted in the P-7 Interstage

Launch Operations

Figures 7 through 15 document the various phases of operations for the two Prospector 7 flights that occurred on 29 October 2006. These took place in the Mojave desert with on-site support and regulatory compliance handled by the non-profit Friends of Amateur Rocketry, Inc. (FAR). Turn-around operations in general took less time than estimated beforehand, with one notable exception being an extra 30 minutes between flights that were spent on an unsuccessful effort to resolve issues with the Wi Fi-based telemetry experiment.

Weather conditions were near-perfect and all systems functioned nominally on the first flight of the day, with the P-7 reaching an altitude on the order of 4500 feet above ground level. The only serious technical issue arose after the first flight, when it was found that there was insufficient helium remaining to pressurize the vehicle for the second flight. A decision was made to switch to nitrogen instead, with the launch team fully recognizing and accepting that this change increased the risk of vehicle failure due to potential propulsion system performance problems. The engine burn did indeed underperform, but the P-7 still managed to achieve a sufficient altitude so that the recovery system functioned nominally. From an operational perspective, the change was transparent and the corrective action is to increase the helium supplies on future tests.

This ability to accept such a high level of risk of vehicle failure and to make such a decision in real time was the single most important factor to achieving all the pre-test goals. It simply would not have been possible on a more traditional aerospace test program.



Figure 7. P-7A Undergoing Final Launch Preparations



Figure 8. First Flight of the Day



Figure 9. P-7A Parachute Deployment



Figure 10. P-7A Landing



Figure 11. Preparations Underway for Second Launch



Figure 12. Second Flight Underway



Figure 13. P-7B Just Prior to Landing



Figure 14. P-7B After Landing



Figure 15. Returning the P-7B to the Launch Site

V. Next Steps

Post-flight inspections back in the CSULB lab confirmed the initial in-the-field assessment that the P-7 could be returned to flight status with a of minimum refurbishment. Consequently, it was utilized on its third flight on 29 April 2006 (Figure 16) to manifest an Iridium-based launch tracker experiment.⁸



Figure 16. On its Third Flight, the P-7 Manifested a Launch Hardware Tracking System

Future plans for the P-7 are to continue flying it during a Phase II follow-on to the SBIR project documented here. Applications will include the pathfinding of operationally responsive spacelift activities at alternative launch sites, while still manifesting academic and launch-related technology experiments. This Phase II work also includes development and the initial deployment of the Prospector 9 (P-9) prototype RLV, which will be a higher performance successor to the P-7. The P-9 will be used in part to assess hybrid launch vehicle (HLV) configurations, in which the first stage is reusable and the second stage is expendable. Such HLV concepts are now the subject of Air Force study.⁹

VI. Conclusion

The development of a prototype RLV demonstrator in just six months, culminating in a set of two flight tests within a period of just 3.5 hours from an unprepared dry lake bed after just 18 hours of on-site activities, demonstrates that responsive, fast turn-around RLV operations are possible with existing technologies and operational constraints. The challenge is to maintain this level of responsiveness as both vehicle performance and fidelity to orbital missions increase. A key factor to ultimately reaching such a fully operational RLV is that risk must be recognized and accepted as an inherent element of the development program. Managing such risk incrementally reduces overall program susceptibility to any one particular failure - a fact the early rocket pioneers fully understood and appreciated.

Acknowledgments

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